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NONDESTRUCTIVE CHARACTERIZATION OF DAMAGED BONDS

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INTRODUCTION

This paper presents a new technique to characterize the damage of a bonded component. The theoretical analysis models a damaged bond as a random distribution of small interphase cracks and cavities. Interaction of ultrasonic waves with these interfacial cracks are studied by a differential self-consistent scheme (DSS) in conjunction with the backscattering signal strength formula [1]. Here the multiple scattering problem from a distribution of interphase cracks is reduced to finding the crack opening displacement of a single interphase crack. Transmission coefficients are obtained explicitly in terms of the characteristic length, density of the interfacial defects and incident wave frequency, from the solution of a first order, ordinary differential equation. Experimental verification of the theoretical solution is performed on aluminum blocks joined by an epoxy layer with varying densities of interfacial cracks. Transmission coefficients from the epoxy layer are measured with a heterodyne interferometer. The measured transmission signals are compared to predicted values and information such as defect distribution and size is extracted.

THEORETICAL MODEL

The theoretical model develops a solution for the interaction of a uniform distribution of interphase cracks with normal incidence, longitudinal waves. Fig. 1. shows a distribution of cracks along the interphase, $x_2=0$, interacting with the displacement components of the incident, u_i^{in}, reflected, u_i^r and transmitted, u_i^t waves. The upper and lower half-spaces have identical material constants, λ and μ, with a mass density, ρ. Far away from the cracks, the displacement components

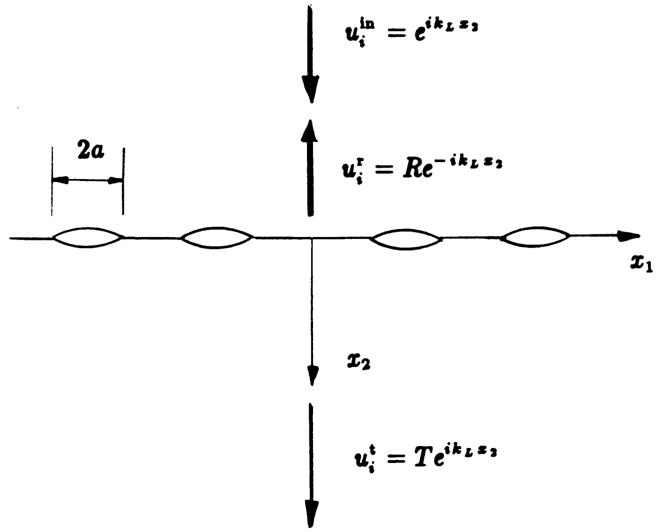

Fig. 1. Interphase cracks interacting with incident, reflected and transmitted waves

can be written as:

$$
\begin{aligned}
u_i &= u_i^{in} + u_i^r \qquad && x_2 < 0 \\
u_i &= u_i^t && x_2 > 0
\end{aligned}
\tag{1}
$$

where the displacement components of the incident, u_i^{in}, reflected, u_i^r and transmitted, u_i^t waves are defined as:

$$
\begin{aligned}
u_i^{in} &= e^{ik_L x_2} \\
u_i^r &= Re^{-ik_L x_2} \\
u_i^t &= Te^{ik_L x_2}
\end{aligned}
\tag{2}
$$

Here R and T are the unknown reflection and transmission coefficients, respectively and k_L is the longitudinal wave number. Please note that the time dependence term, $\exp(-i\omega t)$ (where ω is the frequency), is common in all terms and is omitted throughout the paper.

AULD'S FORMULA FOR BACKSCATTERING

The signal strength formula derived by Auld [1] is used to obtain the backscattering from a perfect interphase and from a single crack in an effective interphase. These two results are combined to calculate the backscattered signal from a distribution of cracks in an effective interphase.

For a two transducer system, Auld [1] has derived a steady-state reciprocal relation which can be applied for flaw detection and characterization. Transducer I with power P produces the incident field and transducer II is the receiver. The ratio of the received electrical signal strength to the incident signal strength is denoted by Γ. Auld's formula gives the change in Γ due to the scattering by an imperfection. For backscattering by an inhomogeneity:

$$
\delta\Gamma = -\frac{i\omega}{4P}\int_S (\sigma_{kj}^{(2)}u_k^{(1)} - \sigma_{kj}^{(1)}u_k^{(2)})n_j dS \tag{3}
$$

where S is an arbitrary surface which surrounds the scatterer and n_j is the unit normal of the surface, pointing inward. The superscript (1) terms are the fields caused by the exciting transducer I with power P in the absence of the scatterer, while the superscripts (2) terms are the fields in the presence of the scatterer. If the scatterer is a traction free crack, Eq. (3) can be further simplified to:

$$\delta\Gamma = \frac{i\omega}{4P}\int_{A^+} \sigma_{kl}^{(1)} \Delta u_k^{(2)} n_l dS \tag{4}$$

where A^+ is the crack area and:

$$\Delta u_i^{(2)} = u_i(x_2^-) - u_i(x_2^+)$$

Eqs. (3) and (4) are used to calculate the backscattering from an interphase and a single crack on an effective interphase.

BACKSCATTERING FROM AN INTERPHASE

Assume an interphase exists along $x_2=0$ as shown in Fig. 2. Here C is the density of crack distribution, given by:

$$C = \frac{aN}{L} \tag{5}$$

where N is the number of cracks in length L, and $2a$ is the crack length. By treating the array of cracks as an interphase, the total field for $x_2<0$ is given by:

$$\begin{aligned} u_i &= u_i^{\text{in}} + u_i^{\text{r}} \\ &= e^{ik_L x_2} + Re^{-ik_L x_2} \end{aligned} \tag{6}$$

By treating the entire lower half-space as a scatterer, Auld's formula becomes:

$$\delta\Gamma = -\frac{i\omega}{4P}\int_{-\infty}^{+\infty} (\sigma_{22}^{(2)} u_2^{(1)} - \sigma_{22}^{(1)} u_2^{(2)})_{|x_2=0} dx_1 \tag{7}$$

where, the incident field (solution in the absence of the scatterer) becomes:

$$\begin{aligned} u_2^{(1)} &= u_2^{\text{in}} = e^{ik_L x_2} \\ \sigma_{22}^{(1)} &= ik_L(\lambda + 2\mu)e^{ik_L x_2} \end{aligned}$$

and the incident and reflected fields (solution in the presence of the scatterer) are written as:

$$\begin{aligned} u_2^{(2)} &= u_2^{\text{in}} + Re^{-ik_L x_2} \\ \sigma_{22}^{(2)} &= \sigma_{22}^{(1)} - ik_L(\lambda + 2\mu)Re^{-ik_L x_2} \end{aligned}$$

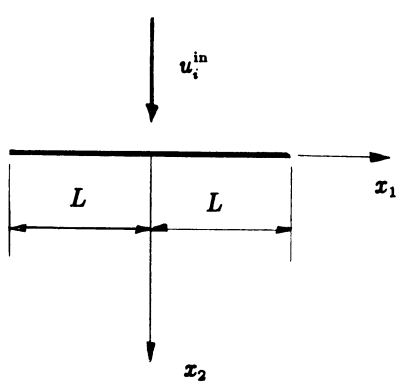

Fig. 2. Array of cracks along x_1

The limits of the integral in Eq. (7) are from $-L$ to $+L$, and Eq. (7) is evaluated in closed form to obtain:

$$\frac{4P}{i\omega}\delta\Gamma = 4ik_L RL(\lambda + 2\mu) \tag{8}$$

Note that R is now a function of C.

BACKSCATTERING FROM A SINGLE CRACK IN AN EFFECTIVE INTERPHASE

For a single crack in an effective interphase scatterer, Auld's formula is:

$$\delta\Gamma = \frac{i\omega}{4P}\int_{-a}^{+a} (\sigma_{22}^{(1)}\Delta u_2^{(2)})_{|x_2=0}\, dx_1 \tag{9}$$

where the solution in the absence of the scatterer (the interphase without the crack) becomes:

$$\begin{aligned}\sigma_{22}^{(1)} &= \sigma_{22}^{\mathrm{in}} + \sigma_{22}^{\mathrm{r}} \\ &= ik_L(\lambda + 2\mu)e^{ik_L x_2} - ik_L(\lambda + 2\mu)Re^{-ik_L x_2}\end{aligned}$$

and the solution in the presence of the scatterer (both the single crack and the interphase) are written as:

$$\begin{aligned}\Delta u_2^{(2)} &= (1 - R)\Delta u_2^{\mathrm{s}} \\ \Delta u_2^{\mathrm{s}} &= \text{COD due to } u_i^{\mathrm{in}} = e^{ik_L x_2}\end{aligned}$$

Now Eq. (9) becomes:

$$\frac{4P}{i\omega}\delta\Gamma = iak_L(\lambda + 2\mu)(1 - R)^2 V \tag{10}$$

with:

$$V = \int_{-1}^{+1} \Delta u_2^{\mathrm{s}}(a\xi)d\xi \tag{11}$$

which must be evaluated numerically.

DIFFERENTIAL SELF-CONSISTENT SCHEME

The differential self-consistent scheme (DSS) has been used extensively in the micromechanics of composite materials. Here, it is used to derive a differential equation for the effective reflection coefficient, *R(C)*, for the scattering due to multiple cracks in an interphase [2]. The DSS is based on the idea of incremental construction of the backscattering amplitude by adding one crack at a time. The fundamental assumption of the DSS is that when an additional crack is added to the interphase, the change in backscattering due to this addition is the backscattering from a single interphase crack. This procedure results in an initial value problem for the effective reflection coefficient, *R*. The solution is accomplished by considering the solution to three problems:

Problem 1: Assume the interphase has $N+1$ cracks in a $2L$ interval for a crack density $C_1=a(N+1)/L$. Now the backscattering, from Eq. (8), is given by:

$$\delta\Gamma(C_1) = \frac{i\omega}{4P}[4ik_L R(C_1)L(\lambda + 2\mu)] \tag{12}$$

Problem 2: Assume a crack density of $C=aN/(L-a)$, for a backscattering of:

$$\delta\Gamma(C) = \frac{i\omega}{4P}[4ik_L R(C)L(\lambda + 2\mu)] \tag{13}$$

Problem 3: Assume a crack of length $2a$ is located on an interphase having a reflection coefficient $R(C)$, where $C=aN/(L-a)$. The DSS states that the backscatter from $N+1$ cracks is the sum of the backscatter from N cracks and the backscatter from one crack located on an effective interphase with a crack density of $C=aN/(L-a)$. This yields, from Eqs. (12), (13) and (10):

$$\delta\Gamma(C_1) = \delta\Gamma(C) + iak_L(\lambda + 2\mu)(1 - R(C))^2 V(\frac{i\omega}{4P}) \tag{14}$$

Substitution and simplification yields:

$$\frac{dR}{dC} = \frac{V(1-R)^2}{4(1-C)} \tag{15}$$

Which is an ordinary differential equation with boundary condition:

$$R(0) = 0 \tag{16}$$

The solution for the reflection coefficient is:

$$R = \frac{-V\ \ln(1-C)}{4 - V\ \ln(1-C)} \tag{17}$$

While the solution for the transmission coefficient is:

$$T = 1 - R = \frac{4}{4 - V\ \ln(1-C)} \tag{18}$$

EXPERIMENTAL PROCEDURE

The experimental procedure, which examines the transmission of elastic waves through an interphase with a known distribution of cracks, is used to verify the theoretical model. This procedure examines epoxy bonded aluminum plates with varying values of crack density in the epoxy. The frequency of the elastic waves, which are generated with a contact, 1MHz piezoelectric transducer, are varied and the transmission coefficients, $T(C)$, are measured with a heterodyne interferometer (Fig. 3.). This non-contact, optical device, is described in [3].

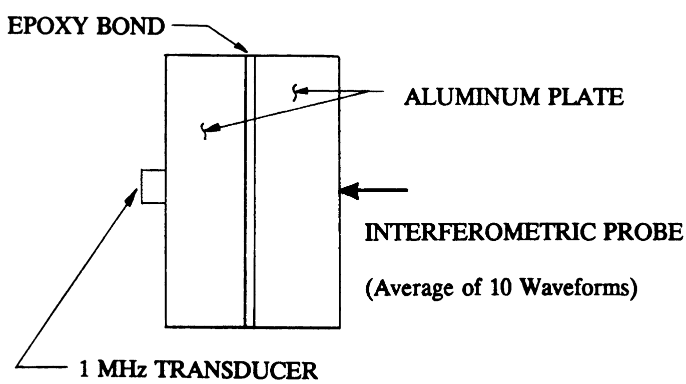

Fig. 3. Epoxy specimen with generation and detection setup

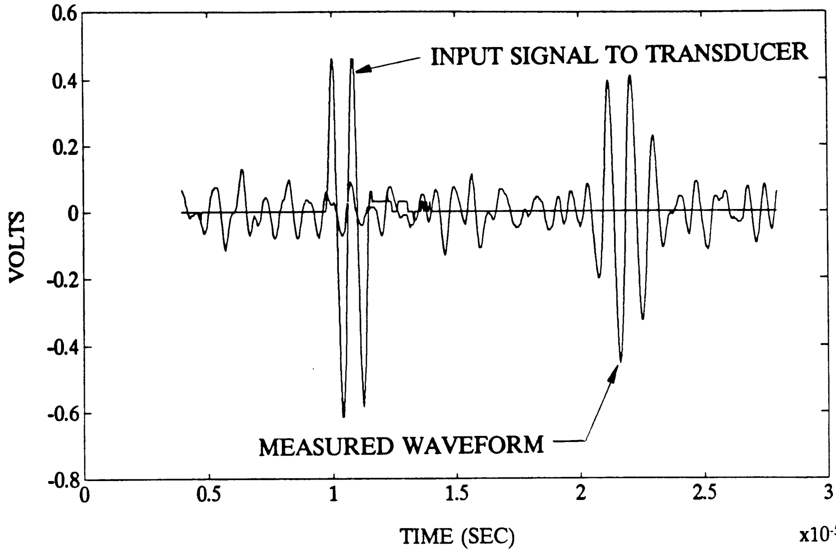

Fig. 4. Measured waveform and input voltage to generating transducer

The specimens are made by joining two 3inx3inx1in 6061 aluminum plates together. Four specimens are manufactured with crack length, $2a$, of 0.059in, and crack density, C, of 0%, 10%, 20% and 30%. The measured signals are averaged over ten input signals to increase the signal-to-noise ratio. Fig. 4 shows a typical measured waveform along with the double pulse input into the generating transducer. The delay time of 10.8μsec agrees with the calculated time of flight through 2in of aluminum and the .05in epoxy bond.

Table 1 is a summary of the measured transmission coefficients, T, for each specimen as a function of wave frequency. Here k_T is the transverse wave number. These transmission coefficients are calculated by normalizing the measured peak-to-peak amplitudes of the 10%, 20% and 30% specimens to the measured peak-to-peak amplitudes of the 0% specimen for each input frequency.

Table 1. Experimentally measured transmission coefficients

Frequency (MHz)	k_Ta	T for C=10%	T for C=20%	T for C=30%
0.8	1.216	0.52	0.72	0.33
0.9	1.368	0.46	0.68	0.32
1.0	1.520	0.48	0.53	0.25
1.1	1.672	0.46	0.52	0.26
1.2	1.824	0.57	0.34	0.32

The experimentally measured transmission coefficients are compared to the theoretical values, calculated from Eq. (18), in Fig. 5. Overall, the measured values are much lower than the predicted values and there is a decreasing trend in the transmission coefficients for increasing number of cracks (increasing *C*). The exception is the 20% specimen, which shows some values larger than those of the 10% sample. There is a problem with the quality of the 20% specimen and these values can be discarded. The difference between the experimental and theoretical results is probably due to loses through the epoxy layer; this material is not considered in the theoretical development. The limitation of the present theoretical model is that the bond's thickness must be much smaller than the wavelength of the incident wave.

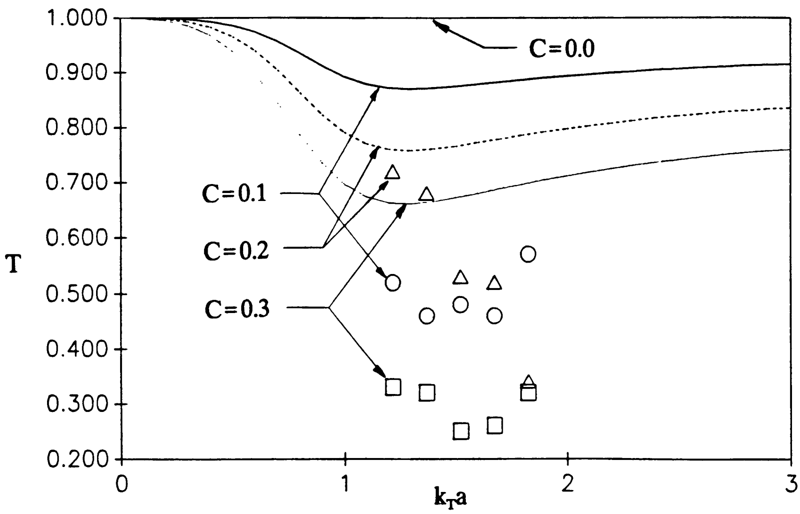

Fig. 5. Comparison of theoretical and experimental results

CONCLUSIONS AND FUTURE WORK

This study develops a theoretical procedure to characterize the damage of a bond and attempts to verify these results with an experimental model; there is agreement in general trends between the theoretical and experimental results. Additional work is necessary to improve the manufacture of the experimental samples. One possible solution is the elimination of the second material, the epoxy bond, which is not considered in the theoretical model and is the probable cause of the lower experimental values. The epoxy could be removed by producing both the bond and the base sample from the same material. Another improvement is to increase the frequency range in the experimental study through the use of a broad band piezoelectric transducer. The theoretical model can be improved by including the effect of the interphase.

ACKNOWLEDGEMENTS

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REFERENCES

1. B. A. Auld, *Wave Motion*, 1, 3 (1979).
2. J. Qu, "Elastic Wave Scattering by an Interface Crack", submitted to *International Journal of Solids and Structures*, 1992.
3. D. A. Bruttomesso and L. J. Jacobs, "Development of a Heterodyne Interferometer with Applications for Acoustic Emission Testing", submitted to *Journal of Engineering Mechanics*, 1992.